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PG 1002+506: a Be Star Apparently at Z > +10 kpc

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ABSTRACT

PG 1002+506 is found to be a Be star, one of two so far found by the Palomar-Green survey. Its spectrum is classified as a B5 $\pm$ 1 Ve, with $T_{\rm eff} = 14,900 \pm 1200$, $\log g = 4.2 \pm 0.2$, and $v \sin i = 340 \pm 50$ km s^{-1}. At $b = +51°$, its height above the Galactic plane would therefore be $Z = +10.8$ kpc, putting this apparently young, rapidly rotating star well into the Galactic halo. Its heliocentric radial velocity is found to be -2 ± 15 km s^{-1}, consistent with either having been formed in the Galactic disk and subsequently ejected, or having been formed in the halo.

1. Introduction

PG 1002+506 was discovered by the Palomar-Green UV-excess survey (Green, Schmidt, & Liebert 1986) and listed as a cataclysmic variable (CV). During a study of the CVs from this survey, Ringwald (1993) obtained ultraviolet and red spectra, and tentatively reclassified it as a detached subdwarf binary, noting Hα in strong emission, unresolved at 10-Å resolution. Several puzzling aspects were noted, however, including the near-constancy of the radial velocities throughout two nights, consistent with no change other than that attributable to atmospheric dispersion in an unrotated slit. There was also no significant variation in the equivalent width of Hα, which one might expect if this were a detached CV progenitor with the hot component irradiating the facing hemisphere of its companion.

That PG 1002+506 is not a CV was shown definitively by E. L. Robinson (1995, private communication): it does not flicker, or have the erratic variability ubiquitous in CVs. This was found with high-speed simultaneous *UBVR* photometry taken in 1995 June with the Stiening photometer on the McDonald Observatory 2.1-m telescope. In 25 min of photometry with 1-s time resolution, all bands showed peak-to-peak amplitudes of $< 2\%$.

This and further spectra have forced another reclassification of this star, as a high-latitude Be star. This is one of two known in the Palomar-Green catalog, the other being PG 0914+001 (Saffer et al. 1997). An Oe star from this survey is also known, PG 2120+062 (Moehler, Heber, & Dreizler 1994).

For reviews on Be stars, see Jaschek & Jaschek (1987) and Slettebak (1988). About one in five non-supergiant B stars shows emission, mainly in Hα but sometimes also in Hβ and higher Balmer lines. Struve (1931) attributed this to a disk, extruded by the star's rotation near the breakup velocity, $\sqrt{GM/R}$. What excites the emission in Be stars is a long-standing mystery, however, as is their evolutionary status. Although Be stars often have an IR excess, PG 1002+506 is not an IRAS source (Neugebauer et al. 1988).

2. Blue spectrum

A blue spectrum (Figure 1) was taken in service time with the Intermediate Dispersion Spectrograph on the Isaac Newton Telescope on La Palma. This 1800-s spectrum was taken in photometric conditions in $2''$ seeing, through a $1.73''$ slit, and has 1.5-Å (FWHM) resolution. The slit was aligned to the parallactic angle, to avoid atmospheric dispersion effects; the spectrum was taken when PG 1002+506 was nearly overhead, at an airmass of 1.08.

A spectral classification of B5 $\pm$ 1 V was arrived at by comparing this spectrum to model atmospheres (Kurucz 1979) and published spectra (Jacoby, Hunter, & Christian 1984; Jaschek & Jaschek 1987). That this is a main-sequence star and not a subdwarf is shown by the presence of the H13 and 14 lines. That it is not a giant or supergiant is shown by the widths of its Balmer lines, with FWZI of Hγ of 31 ± 3 Å. There is no spectroscopic evidence that this star is a binary.

3. Radial Velocity

On 1997 January 3 UT, two 10-min exposures were obtained with the Modular Spectrograph on the 2.4-m Hiltner Telescope at Michigan-Dartmouth-MIT Observatory, Kitt Peak, Arizona. The spectra covered from 4650 to 6727 Å, and had 4-Å (FWHM) resolution. The weather was poor, with $> 1''$ seeing and rising humidity that forced a shutdown just after these spectra were taken. The spectrograph slit was set at the parallactic angle, even though PG 1002+506 was only one hour east of the meridian. The $1''$ slit projected to 3 Å on the detector. With the mediocre seeing, we expect "slit-painting" velocity errors to be small, probably < 5 km s^{-1}, based on experience with similar sharp lines in white dwarf/red dwarf binaries (Thorstensen, Vennes, & Shambrook 1994). The exposures were bracketed by HgNeXe exposures, for which the RMS residual was < 0.05 Å, and the maximum residuals for the weakest lines were < 10 km s^{-1}. Most lines had residuals around 2 km s^{-1}.

Hα appears to be slightly resolved, and is in strong emission (see Figure 2), with an equivalent width of 17.8 ± 0.3 Å and FWHM of 580 ± 30 km s^{-1}. There is also emission in the core of Hβ. By convolving Hα with the derivative of a Gaussian with FWHM = 8 Å and taking the zero of the convolution as the velocity (Schneider & Young 1980), we find heliocentric radial velocities of the spectra taken at HJD 2450451.90425 and 2450451.91140 of +29.3 and +28.9 km s^{-1}, respectively. The velocities of the O I λ6300 Å night sky line were 1.6 and 0.7 km s^{-1}, showing the accuracy of the wavelength scale.

However, the emission lines in Be stars are well

known to be variable in profile over timescales of days or longer, and are therefore not reliable indicators of the systemic velocity. The spectra were therefore summed together and rectified, to remove continuum slope effects. The radial velocity was then measured from the absorption wings of Hα by convolving a positive and a negative Gaussian with the line profile and taking the zero of this convolution as the velocity (Schneider & Young 1980). In all cases the Gaussians had 4 channels FWHM. The separation between the Gaussians was varied, from 24 to 20 to 16 Å; the corresponding heliocentric radial velocities are -2.0, -0.5, and -4.1 km s^{-1}. Finding the line's centroid by fitting and subtracting a linear approximation of the continuum, numerical integration of the intensity, and taking the centroid (crudely, with the IRAF *splot* 'e' command) gave $+0.4$ km s^{-1}. We conclude that PG 1002+506 has a heliocentric radial velocity of -2 ± 15 km s^{-1}.

4. Model atmosphere analysis

We have performed a model atmosphere analysis of the blue optical spectrum to estimate the atmospheric parameters $T_{\rm eff}$ and log g, as well as the projected stellar rotation velocity $v \sin i$. Our grid of synthetic spectra was calculated with the radiative transfer code SYNSPEC (Hubeny, Lanz, & Jeffrey 1995), assuming the temperature and pressure stratifications of Kurucz (1991). The metal and helium abundances were held fixed at the solar value. At the temperature and surface gravity of spectral type B5V, the assumption of LTE is well justified. The temperature and gravity grid points were $T_{\rm eff} = 13{,}000 - 17{,}000$ K in steps of 1,000 K, and $\log g = 3.5 - 5.0$ in steps of 0.5 dex. In addition each model was convolved with a rotational broadening function at projected rotation velocities $v \sin i = 50 - 350$ km s^{-1} in steps of 50 km s^{-1} to produce a 3-dimensional fitting grid. The stellar parameters were estimated by simultaneous variation using a non-linear χ^2 minimization algorithm. Details of the synthetic spectrum calculations and the fitting algorithm are given by Saffer et al. (1994) and Saffer et al. (1997). Due to the partial filling in of the lower Balmer lines by emission from the circumstellar material, we have restricted the analysis to the portion of the spectrum blueward of Hβ.

The best-fit stellar parameters are $T_{\rm eff} = 14,900 \pm 1200$ K, $\log g = 4.20 \pm 0.2$, and $v \sin i = 340 \pm 50$ km s^{-1} (see Figure 1). The quoted 1-σ errors are based on counting statistics and account for covariance for the fitting parameters; they also estimate systematic errors.

5. Evolutionary status

The effective temperature, surface gravity, and very high rotational velocity are fully consistent with a spectral classification of B5Ve. The breakup velocity expected for this star is 540 km s^{-1}. The fit places this star in the area of confusion in the $T_{\rm eff}/\log g$ diagram where the Population I main- sequence intersects the Population II blue horizontal branch (BHB) (Schönberner 1993; Bertelli et al. 1994). For example, PG 0832+676 at first appeared to be a young star far from the Galactic plane, but turned out to be a nearby blue evolved star, upon analysis of high-resolution spectra (Hambly et al. 1996). However, identification of PG 1002+506 as a BHB star is contradicted both by the emission reversals in the Hα and Hβ absorption lines, and by its high rotation velocity, since BHB stars are slow rotators (Peterson, Rood, & Crocker 1995).

Assuming PG 1002+506 to be of Population I origin, we used the derived atmospheric parameters and the evolutionary tracks of Claret & Gimenez (1992) to estimate the stellar mass and evolutionary age (see Table 1). A distance estimate was obtained from the absolute visual magnitude deduced from the stellar mass, atmospheric parameters, and bolometric corrections of Kurucz (1979). PG 1002+506 has $B = 15.36$ (Green et al. 1986). Assuming $B - V = -0.16$ for B5V stars (Allen 1973), and a reddening $E(B - V) < 0.01$, inferred from the map of Burstein & Heiles (1982), this would imply a distance of 13.9 kpc, which for a Galactic latitude $b = 51°$, corresponds to a z-distance of 10.8 kpc above the Galactic plane. Although large, this is not unheard of (Kilkenny 1992). For a Galactic longitude $l = 165°$, this would imply a galactocentric radius of 17.1 kpc, putting PG 1002+506 at the outskirts of the Galaxy.

6. Kinematical analysis

As the existence of young objects at large distances from the star forming regions of the Galactic disk is potentially interesting, we have performed a kinematical analysis for PG 1002+506. Although no proper motion information is available, it is possible to use the observed radial velocity of a star to constrain its evolutionary history. A detailed description of the

method of analysis is given by Rolleston et al. (1997).

We first consider a scenario whereby PG 1002+506 has a zero velocity component parallel to the Galactic disk, and ejection has occurred perpendicular to the plane of the Galaxy. We have corrected the observed heliocentric velocity for the effects of differential rotation (Fich et al. 1989), assuming that the halo corotates with the disk, to determine the stellar radial motion (v_r) with respect to a standard of rest defined by its local environment. Our initial assumption implies that the observed radial velocity is a component of the stellar space motion (v_z) perpendicular to the disk. We then attempt to show that PG 1002+506 could have reached its present position in the Galactic halo within its evolutionary lifetime, while reproducing the observed radial velocity, and calculating the required ejection velocity. These calculations have adopted the gravitational potential function of House & Kilkenny (1980). This analysis implicitly assumes that the star is ejected from the disk shortly after birth, consistent with cluster ejection simulations.

The results of the kinematical analysis are given in Table 1. Given the large z-distance, it is not surprising to find the "time of flight" to be larger than the evolutionary age. We have therefore considered the effects of errors in the derived atmospheric parameters and the radial velocity measurement. By optimizing the values of $T_{\rm eff}$ and $\log g$ such that they are self-consistent within the errors, it is possible to increase the evolutionary age, so that it is greater than the predicted flight time. For example, adopting values of $T_{\rm eff} = 13,750$ K and $\log g = 4.0$ would imply an age of 115 Myr for a mass of 4.0 $M_\odot$. Allowing an error of 15 km s^{-1} in the observed heliocentric velocity also decreases the estimated flight time, but not significantly, to 84 Myr.

7. Conclusions

PG 1002+506 appears to be a young, rapidly rotating B5Ve star at a distance of 10.8 kpc from the Galactic plane, and at a galactocentric radius of 17.1 kpc. The kinematical analysis suggests that it could have attained its present Galactic position having been ejected from the disk shortly after its formation. Furthermore, the required ejection velocity of ≈ 230 km s^{-1} can also be produced by the known mechanisms predicted by Leonard (1993). A detailed atmospheric analysis with higher-quality spectra should still be done, to determine abundances and confirm that PG 1002+506 really is a distant main-sequence star, and not a nearby blue evolved star. If PG 1002+506 really is 10.8 kpc from the Galactic plane, interstellar absorption in this same spectrum would probe a line through the Galactic halo otherwise difficult to acquire.

E. Harlaftis took the blue spectrum with the Isaac Newton telescope, which is operated on La Palma by the Royal Greenwich Observatory at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. Michigan-Dartmouth-MIT Observatory is operated by a consortium of the University of Michigan, Dartmouth College, and the Massachusetts Institute of Technology. Thanks also to Rob Robinson, Malcolm Coe, Richard Green, Uli Heber, Gerrie Peters, and Richard Wade, for helpful discussions.

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Table 1

Stellar parameters

$T_{\rm eff}$	$14,900 \pm 1200$ K
$\log g$	4.2 ± 0.2
$v \sin i$	340 ± 50 km s^{-1}
$v_{breakup}$	540 km s^{-1}
Mass	4.2 $M_{\odot}$
Age	50 Myr
l	165.072°
b	50.943°
B	15.36
Distance	13.9 kpc
$R_{galactocentric}$	17.1 kpc
z-distance	10.8 kpc
$v_{heliocentric}$	-2 ± 15 km s^{-1}
v_z	18.0 km s^{-1}
T_{flight}	85 Myr
v_{ej}	229 km s^{-1}
Age (OPT)	115 Myr
v_z (OPT)	39.0 km s^{-1}
T_{flight} (OPT)	84 Myr
v_{ej} (OPT)	249 km s^{-1}

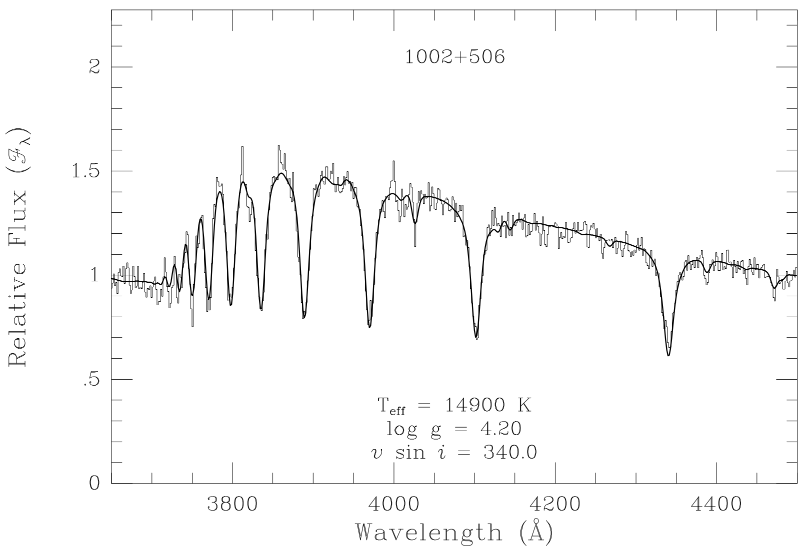

Fig. 1.— Spectrum of PG 1002+506, taken 1994 February 26 UT. The best-fit synthetic spectrum (heavy curve), simultaneously determining $T_{\rm eff}$, $\log g$, and $v \sin i$, is superimposed on the observed spectrum (thin histogram). The core of Hβ showed emission, but was excluded to avoid spoiling the fit.

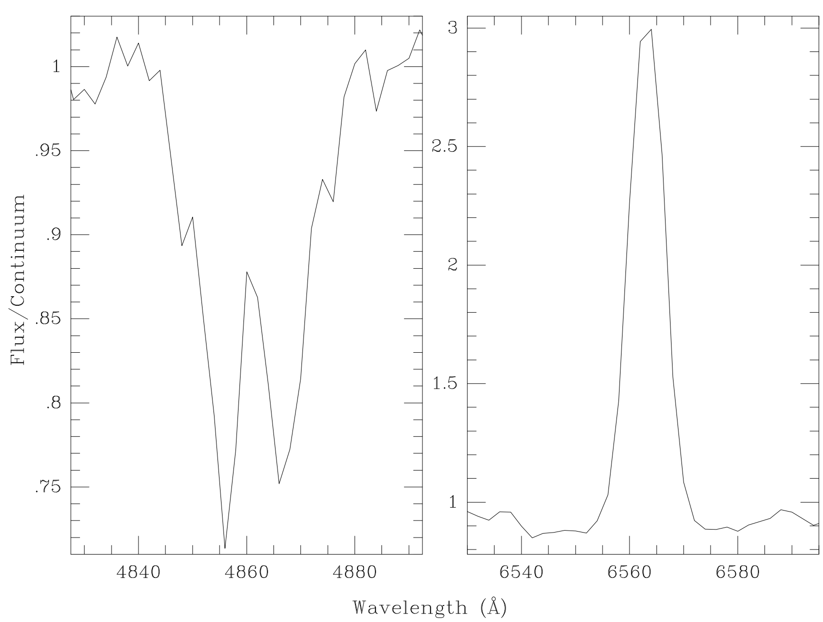

Fig. 2.— Modular Spectrograph profiles of Hβ (left) and Hα (right), at 4-Å resolution, taken 1997 January 3 UT.